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No Evidence Sowing Date Influences Optimum Plant Density of Sweet Corn Grown in the Midwestern United States

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Abstract. **Sweet corn (*Zea mays* L.var. *rugosa* or *saccharata*) is sown across a wide range of dates to provide a steady supply of marketable ears for fresh market and processing. There is a perception in the sweet corn industry that plant density tolerance declines in late-season plantings in the midwestern United States; however, publicly available data to support this perception cannot be found. Using field experiments, the objectives of this research were to quantify the effect of the sowing date on growth responses to plant density and determine the extent to which the sowing date influences the optimum plant density and maximum yield/profit. There were few main effects or interactions of the sowing date on crop growth. More importantly, there was no effect of the sowing date on the economically optimum plant density or plant density that optimized yield. Although variations exist in sweet corn optimum plant densities in the midwestern United States, these variations are likely driven by several factors other than the sowing date that have not yet been fully characterized.**

Sweet corn ears are ripe at the R3 crop growth stage. Because the product is perishable, marketable ears must be harvested in a timely manner. A steady supply of marketable ears is important for both the fresh market to maximize sales period and the processing market because processing facilities have a finite capacity to handle incoming perishable ears. To create a long harvest window during the growing season, the sweet corn industry staggers the sowing dates and, to a lesser extent, uses early-maturing hybrids at the onset of the growing season. In the midwestern United States, the sowing window ranges from early April to early July, resulting in a harvest window from early July to early October.

The sowing date influences sweet corn growth, development, and yield. Williams and Lindquist (2007) observed that the early May-planted sweet corn grew slower and produced a denser canopy compared with late June-planted sweet corn in central Illinois. Across a wide range of sowing dates in the midwestern United States, the rate of leaf appearance and maximum leaf number steadily decreased with later sowing dates (Williams 2008). In Newfoundland (Canada), delayed sowing through May resulted in rapid crop emergence and development (Kwabiah 2004). The sowing date also influences the ability of the crop to compete with weeds. Multiple studies in the midwestern United States have shown that the ability of sweet corn to tolerate weeds improves during the second half of the sowing window (Williams 2006, 2009). Compared with earlier sowings, yield loss from weed escapes is lower for later sowings. Finally, yields of some of the latest-planted sweet corn decline, as evidenced by experimental trials (Williams 2008) and observational data from growers' fields (Williams et al. 2009).

Plant density also has a major influence on sweet corn grown for the fresh market (Morris et al. 2000; Rangarajan et al. 2002) and processing (Williams 2012, 2018). Commercially available hybrids vary widely in plant density tolerance (Williams 2015), which is defined as the ability of the crop plant to maintain yield under crowded conditions. Plant density tolerance is a heritable trait (Shelton and Tracy 2013). Some of the most recent research shows that hybrids with superior density tolerance are being underplanted in the midwestern United States (Dhaliwal and Williams 2019). Motivated by an interest in growing sweet corn more sustainably, the sweet corn industry is moving toward the greater availability and use of density-tolerant hybrids and growing them at densities that optimize performance (Quinn 2019).

Does the sowing date influence optimum plant density? The extent to which the sowing date interacts with the crop response to plant density, including optimal plant densities, is unknown. Previous studies of the plant density evaluated the crop response to plant density within a narrow range of sowing dates. In the sweet corn industry, there is a perception that plant density tolerance declines in late-season plantings in the midwestern United States (personal communication); however, publicly available data to support this perception cannot be found. Therefore, the objectives of this research were to quantify the effect of the sowing date on growth responses to plant density and determine the extent to which the sowing date influences optimum plant density and maximum yield or profit of sweet corn grown in the midwestern United States.

Materials and Methods

Field experiments were conducted using a single protocol in 2018, 2019, and 2020, at the University of Illinois Vegetable Crop Research Farm near Urbana, IL. The dominant soil was a Flanagan silt loam (fine, smectitic, mesic Aquic Argiudolls) with an average of 3.2% organic matter and pH of 5.7. A different field was used each year, and the preceding crop was soybean. Within 24 h of each sowing date, a preemergence treatment comprising atrazine, mesotrione, and s-metolachlor plus 168 kg/ha of liquid nitrogen was applied to appropriate plots and incorporated with two passes of a field cultivator. Tefluthrin was applied using a t-band at sowing to control corn rootworms (*Diabrotica* spp.).

Experimental approach. The experimental design was a split-split plot arrangement within a randomized complete block with four replications. The levels of the main plot were four sowing dates representing early, mid, late, and very late sowing for the midwestern United States (Table 1). Main plots were separated by 1.5-m alleys. Three-meter-wide main plots consisting of four 0.76-m-spaced rows were divided into 20.1-m-long subplots and assigned one of four of the following target plant densities: 4.3, 6.5, 8.6, or 10.8 plants/m^2. Plant densities were established by overseeding the crop ~30% with a four-row planter (Cone Plot Planter; Almaco, Nevada, IA) and hand-thinning to target

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Table 1. Timeline of important events, daylength at the time of mean silking, and cumulative growing degree days (GDDs) and water supply.

							Cumulative GDDs			Cumulative water supply		
Sowing treatment	Yr	Sowing date (DOY)	Mean silking date (DOY)	Harvest date (DOY)	Daylength at mean silking date (h)	Total days sowing to harvest (d)	Sowing to mean silking (GDDs)	Mean silking to harvest (GDDs)	Sowing to harvest (GDDs)	Sowing to mean silking (cm)	Mean silking to harvest (cm)	Sowing to harvest (cm)
Early	2018	117	176	198	15.0	82	737	354	1,091	30.7	5.6	36.3
	2019	115	189	211	14.9	97	769	341	1,110	30.4	3.9	34.2
	2020	113	[i]									
Mid	2018	134	185	204	14.9	71	763	254	1,017	28.8	4.0	32.7
	2019	137	195	217	14.8	81	759	327	1,086	21.5	3.3	24.7
	2020	133										
Late	2018	156	206	226	14.5	71	749	273	1,022	23.8	2.5	26.3
	2019	154	209	231	14.4	78	787	312	1,099	16.8	3.9	20.7
	2020	153										
Very late	2018	180	229	249	13.7	70	723	297	1,021	13.1	5.2	18.2
	2019	177	226	249	13.8	73	762	283	1,045	13.1	6.2	19.3
	2020	177										

[i] On 11 Jul 2020 (DOY 192), as the early sowing treatment was beginning to silk, a severe hail storm destroyed the experiment. DOY = day of the year.

densities at two- to three-collar sweet corn. Plant densities were counted 1 week after thinning to confirm that the intended target densities were established. Subplots were divided into 3-m-wide × 9.1-m long sub-subplots and assigned to one of two hybrids widely used by processors in recent years, specifically DMC 21–84 (Del Monte, Walnut Creek, CA) and GSS 1477 (Syngenta, Wilmington, DE). The crop was kept free of weedy plants by hand-hoeing as needed. Rainfall was supplemented with sprinkler irrigation as needed to avoid crop stress from abnormally low precipitation.

Data collection. At the onset of anthesis, the number of plants with emerged silks were counted daily until 50% of plants had silked; herein, this is identified as the midsilk date. Crop shoot data were collected from the center two rows of each sub-subplot within 10 d after silk emergence. Based on two randomly selected plants per sub-subplot, the total number of leaves were counted, the plant height was measured from the soil surface to the uppermost leaf, and the stem widths of the major and minor axes were measured on the second internode above the soil surface using calipers. At five locations within each sub-subplot, the leaf area index was measured using a ceptometer (AccuPAR Linear Ceptometer; Decagon Devices, Pullman, WA) placed perpendicular to, and centered within, the crop row. Ceptometer measurements of incident light above and below the canopy were used to estimate intercepted photosynthetically active radiation. All ceptometer measurements were performed under full sun conditions and within 2 h of solar noon.

Hybrids were harvested 18 to 21 d after midsilk of plots assigned 4.3 plants/m^2. The area within each sub-subplot harvested was the center 6.1-m length of the center two rows. Marketable ears, identified as larger than 4.4 cm in diameter, were hand-harvested, counted, and weighed. A random sample of 10 ears per sub-subplot were weighed before and after husking with a commercial husking bed (A&K Development). A hand-fed corn cutter (A&K Development) was used to cut fresh kernels off each cob. Cobs were weighed. A 100-g sample of fresh kernels was collected to determine kernel moisture. Fresh kernel mass was determined as the difference between husked ear mass and cob mass, corrected to 76% moisture, and then scaled to the plant and subplot.

Daily minimum and maximum air temperatures and rainfall were obtained from a nearby weather station (Illinois State Water Survey, Champaign, IL). Cumulative growing degree days were determined after crop sowing using a base temperature of 10 °C.

Economic variables. United States processing sweet corn is grown according to a contract between a vegetable processor and a grower; the processor supplies seed of specific hybrids and determines seeding rates. Two economic measures of crop performance were quantified as described by Dhaliwal and Williams (2019). In brief, contract growers are compensated by processors for the mass of green ears harvested; therefore, an important yield metric for the grower is the green ear mass yield. Processors take the complete ears and produce several sweet corn products, most often cases of frozen or canned kernels. An important yield metric for the processor is the value of cases produced from each ton of green ear mass less the cost of contracting with the grower and seed costs. As such, in theory, two types of optimum plant densities exist (Williams 2012, 2018): an optimum plant density yield (YOPD) for the grower and an economically optimum plant density (EOPD) for the processor.

Statistical analyses. All response variables were analyzed with an analysis of variance model using the mixed procedure in SAS (version 9.4; SAS Institute Inc., Cary, NC). Sweet corn hybrid, target plant density, sowing date, and their interactions were considered fixed effects. Year and replicates nested within the year were treated as random effects. Mean comparisons of significant treatment effects were performed using Tukey's mean separation test ($\alpha = 0.05$).

Regression analyses were performed to quantify the effect of plant density on the response variables with significant plant density effects or significant interactions with the sowing date and hybrid. Response variables were fitted to linear or quadratic models as a function of plant density using the ordinary least squares regression.

Separate regression models were fit to model the green ear mass and gross profit margin as a function of hybrid, plant density, and sowing date. The following regression model was used for each study year and replicate:

$$y_{ijkl} = \boldsymbol{\beta_0} + \boldsymbol{\beta_1 H_i} + \boldsymbol{\beta_2 SD_j} + \boldsymbol{\beta_3 PD_k} + \boldsymbol{\beta_4 PD_k^2} + \varepsilon_{ijkl} \qquad [1]$$

where y_{ijkl} is the response variable (i.e., green ear mass or gross profit margin), $\boldsymbol{\beta_0}$ is the model intercept, and $\boldsymbol{\beta_1}$, $\boldsymbol{\beta_2}$, $\boldsymbol{\beta_3}$, $\boldsymbol{\beta_4}$ are the slope coefficients for hybrid ($\boldsymbol{H_i}$), sowing date ($\boldsymbol{SD_j}$), plant density ($\boldsymbol{PD_k}$), and squared plant density ($\boldsymbol{PD_k^2}$), respectively. The peaks (i.e., maximum predicted value) of quadratic curves for each unique combination of year, replicate, hybrid, and sowing date were identified to determine optimum plant densities for the corresponding response variable (green ear mass or gross profit margin). Boxplots were used to show variability in optimum plant densities for the maximum yield and gross profit margin across sowing dates. Variability in the green ear mass and gross profit margin predicted at optimized plant densities for the maximum yield and gross profit margin, respectively, were visualized across the sowing dates using boxplots. Mean comparisons of significant sowing date effects on the variability of optimum plant densities, maximum yield, and maximum gross profit margin were performed using Tukey's mean separation test ($\alpha = 0.05$).

Results

Environmental conditions. A severe hail storm on 11 Jul 2020 destroyed the experiment that year. At the time of the hail storm event, crop growth stages ranged from V2 for the very late sowing date to VT/R1 for the early sowing date. Although the very late sowing date may have recovered from the hail storm injury, other sowing dates were permanently damaged. For instance, the early sowing date was beginning to silk, which is a growth stage particularly sensitive to hail (Battaglia et al. 2019). Because 75% of the experimental units were lost, the balance of the 2020 experiment was deemed a complete loss.

Across sowing dates, several patterns in environmental conditions emerged. As the sowing date progressed, daylength at silking decreased (Table 1). Daylength decreased an average of 2.4 h from the early sowing date to the very late sowing date. Fewer days were required to reach silking for later sowing dates. For instance, the number of days from sowing to silking decreased by an average of 18 d for the very late sowing date compared with the early sowing date (Table 1). A similar pattern was observed for days to harvest. The cumulative water supply decreased across the growing season for later plantings; however, thermal time drives sweet corn development in these irrigated studies, as evidenced by the cumulative thermal time from sowing to harvest remaining constant across sowing dates.

Growth responses. Few interactions were observed between sowing date and plant density on crop growth responses. Plant height after silking was unaffected by plant density until the latest sowing date (Fig. 1). For the very late sowing date, plant height was shortened at a rate of ~2.1 cm for each additional plant/m^2. Otherwise, plant height was relatively consistent across other sowing dates and plant densities.

The sowing date influenced the canopy density. Plants of the two middle sowing dates (mid and late) had greater leaf area indexes than those of the earliest and latest sowing treatments (Fig. 2). For all other growth response variables measured during this research, the sowing date had no main effect or interactive effect on the crop.

Plant density was the main driver of several crop growth traits, including crop development and canopy density, with the hybrid occasionally having a minor effect. The increasing plant density delayed thermal time to silking (Fig. 2A) and increased canopy density and light interception, as evidenced by trends of the leaf area index and intercepted photosynthetically active radiation (Fig. 2C, 2D). For instance, each additional plant/m^2 delayed thermal time to silking by 4.7 growing degree days. The increasing plant density resulted in smaller plant stems. For instance, each additional plant/m^2 reduced the stem diameter by ~0.8 to ~1.0 mm, depending on the hybrid (Fig. 2B).

As expected, the plant density was the main driver of per-plant yield traits. The ear number per plant, green ear mass per plant, and kernel mass per plant were negatively related to plant density (Fig. 3). For instance, kernel mass per plant decreased at a rate of 20.7 g/plant with each additional plant/m^2. Small but significant differences were detected between hybrids in the plant density response of the ear number per plant (Fig. 3A).

Optimum plant density and maximum yield/profit. The sowing date had no effect on the optimum plant density or whether the plant density was optimized for profit to the processor or yield to the grower. Although there appeared to be a slight decrease in optimal plant densities across some sowing dates (Fig. 4A, 4B), these trends were not significant ($P \geq 0.232$).

In contrast, the sowing date affected the maximum yield at YOPD. The maximum yield of the very late sowing treatment was among the lowest, averaging 4.85 Mt/ha less than that of the preceding sowing date (Fig. 4D). Although similar trends were observed for maximum profit at EOPD (Fig. 4C), the effect of the sowing date was not significant ($P = 0.347$).

Discussion

Sweet corn is sown across a wide range of dates to provide a steady supply of marketable ears for fresh market and processing. In the midwestern United States, the sowing window ranges from early April to early July. Across this sowing window, certain environmental conditions change predictably, including shortening daylength at silking. Nonetheless, sweet corn development during this research was driven by thermal time. Because later sowing dates accumulate heat units more rapidly during vegetative growth, days to silking and maturity decrease across the sowing window. This research was conducted to empirically quantify the extent to which the sowing date influences the crop growth response to the plant density, optimum plant densities, and maximum profit to the processor and yield to the grower.

With one exception, the plant density and sowing date independently affected sweet corn growth. The exception was plant height at silking; the plant height decreased with the plant density for the very late sowing date. Although this trend was observed across 2 years, the practical implications are likely minimal. Sweet corn is machine-harvested and the corn header can be adjusted to account for variations in the placement of the ear on the stalk. Plant height generally increased for the latest sowing date compared with the earliest sowing date during previous research (Williams 2008; Williams and Lindquist 2007); however, a closer look at variability in height within the sowing window during previous research and our research suggested that factors influencing height growth are only loosely related to the sowing date.

The sowing date influenced the canopy density. Main-season sowing dates, specifically mid and late, produced the densest canopy. A similar pattern was observed during 1 of 2 years during previous research (Williams 2008); however, a much stronger relationship between the leaf area index or light interception and plant density was observed during the current and previous research (Williams 2012, 2018).

Per-plant yield traits respond sharply to plant density. The present research is consistent with previous research in that increasing plant density results in smaller, shorter ears (Shelton and Tracy 2013; Williams 2012, 2018). Unless ear size decreases below a critical threshold for fresh market standards or

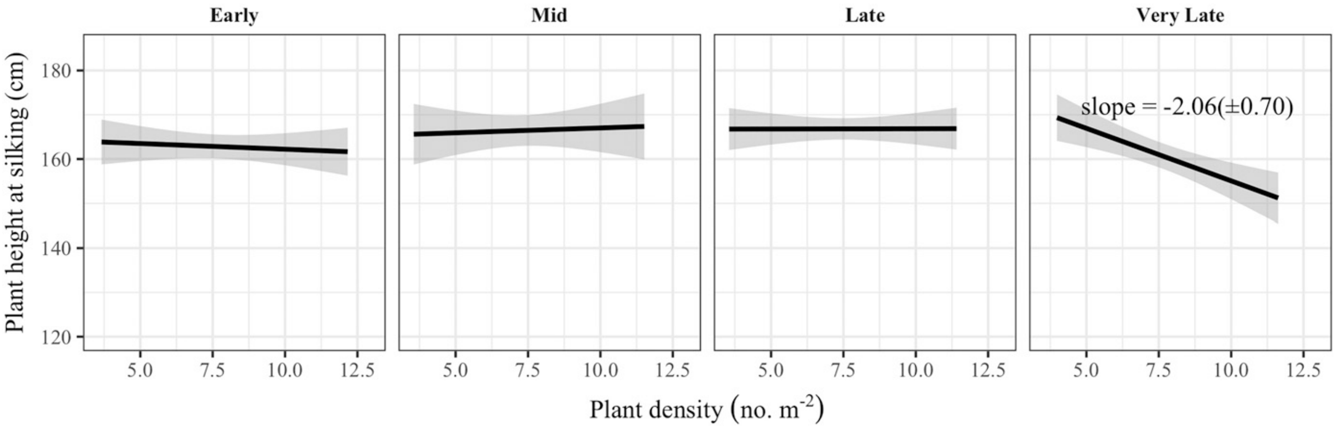

Fig. 1. Best fit line for the relationships between plant density and height at silking for the four sowing date treatments. The 95% confidence intervals are shown by the shaded regions around the line of best fit. Significant ($\alpha = 0.05$) slope estimates from linear regression analyses are shown with *SE* in parentheses.

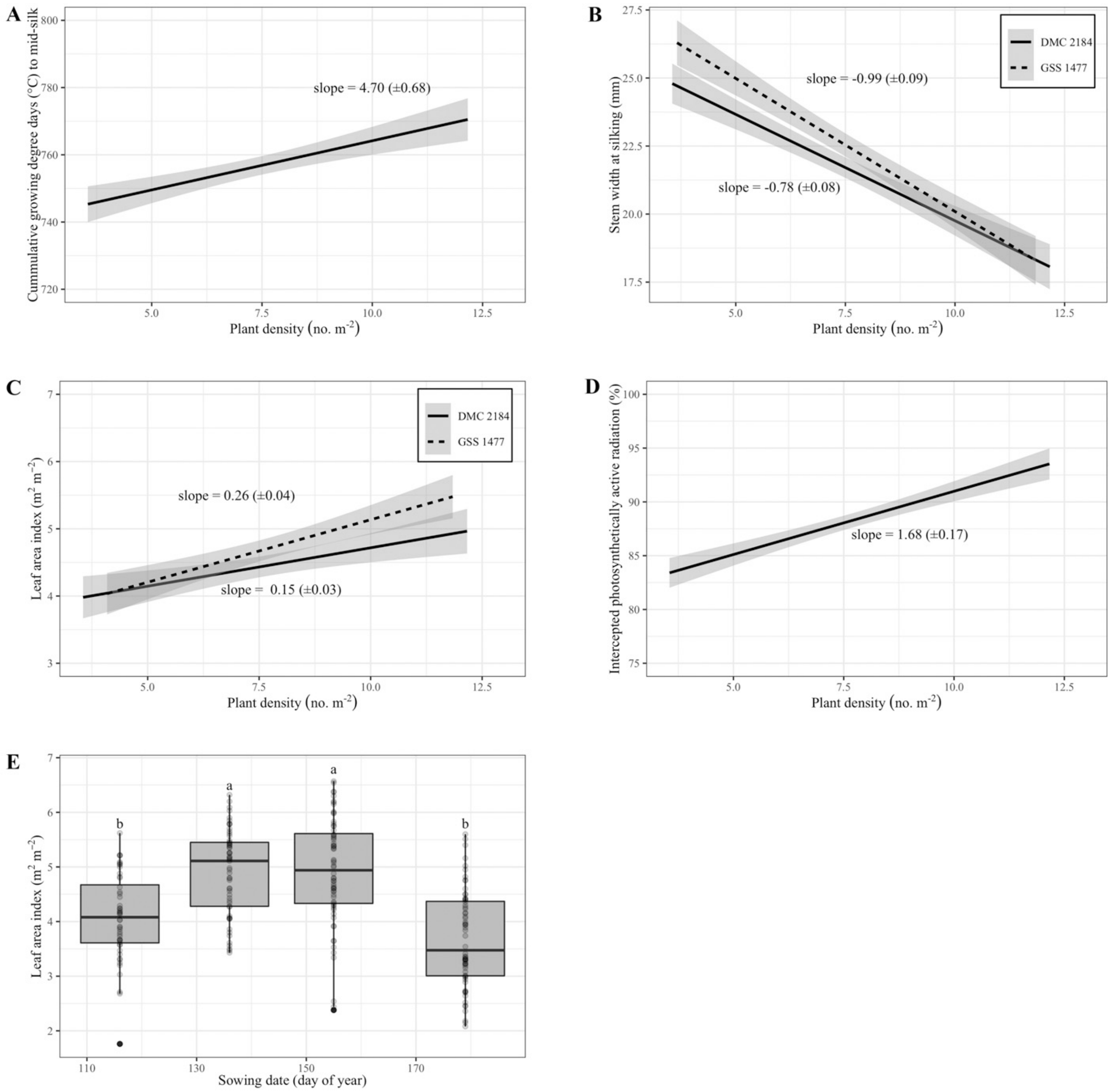

Fig. 2. Best fit line for the relationship between plant density and (**A**) cumulative growing degree days to midsilk, (**B**) stem width, (**C**) leaf area index, and (**D**) intercepted light. Separate models were fit to hybrids when plant density × hybrid interactions were observed ($\alpha = 0.05$). The 95% confidence intervals are shown by the shaded regions around the line of best fit. Slope estimates from linear regression analyses are shown with *SE* in parentheses. Moreover, (**E**) the distribution of the leaf area index at silking for the four sowing dates are represented by boxplots. Sowing treatments with different leaf area indices are identified with unique letters above each boxplot.

efficacy of processing equipment, the yield measured on a per-area basis, instead of per-plant, is most relevant to productivity and profitability in the sweet corn industry (Williams 2014).

This research found no evidence that the sowing date affects the optimum plant density of sweet corn. There were few main effects or interactions of the sowing date on crop growth. More importantly, there was no effect of the sowing date on EOPD or YOPD. This finding is surprising because there is a perception in the sweet corn industry that density tolerance declines in late-season plantings. The authors acknowledge the limitations of the experiment. Perhaps intra-annual and interannual weather variability complicated the detection of an effect of sowing date aimed at 3 years, but only obtaining 2 years, of data. Environmental variability has a large effect on the density response of grain corn (Assefa et al. 2016; Edwards 2016). Perhaps the two hybrids tested, although widely grown, fail to fully represent the sweet corn response to the plant density and sowing date. A wide range of density tolerance is known to exist for historic and modern sweet corn hybrids (Dhaliwal et al. 2021; Williams 2015). Alternatively, perhaps sowing date in the midwestern United States does not affect sweet corn density tolerance. Grain corn response to plant density was unaffected by sowing dates across four weeks in Minnesota (van Roekel and Coulter 2012). In the latter scenario, the perception of losing density tolerance late in the season could reflect the fact that sweet corn planted in the latest sowing dates may have poorer growing conditions that lower yield potential,

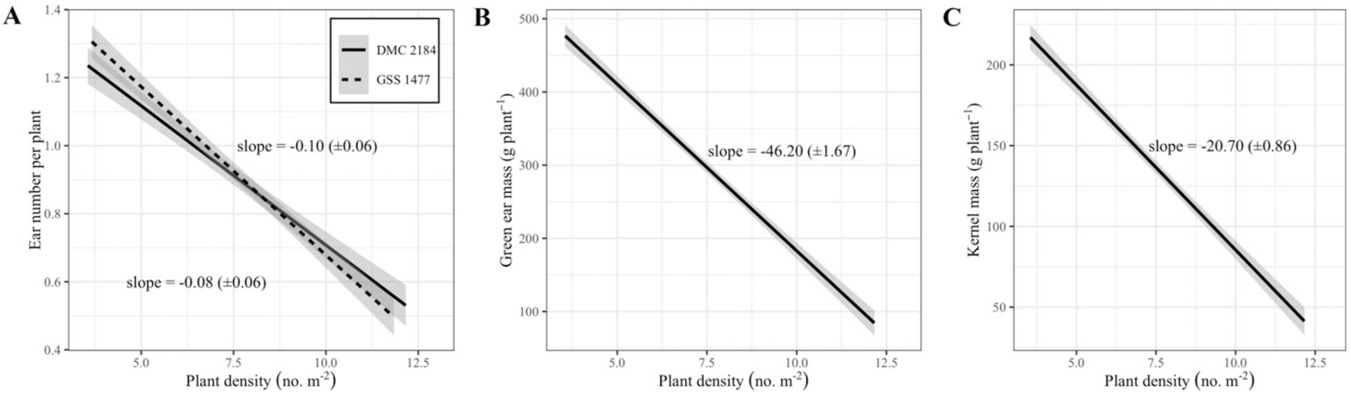

Fig. 3. Best fit line for relationships between the plant density and (**A**) ear number per plant, (**B**) green ear mass, and (**C**) kernel mass. Separate models were fit to hybrids when plant density × hybrid interactions were observed ($\alpha = 0.05$). The 95% confidence intervals are shown by the shaded regions around the line of best fit. Significant slope estimates from linear regression analyses are shown with *SE* in parentheses.

including generally greater incidence of insect pests and diseases as the season progresses (Malvar et al. 2002; Parsons and Munkvold 2012; Straub and Boothroyd 1980). Depending on the weather in rainfed production systems, reduced yield of late plantings could be the result of increased water limitations later in the season. The latest sowing treatments resulted in the lowest yields in the present and previous research (Williams 2008). The occurrence of lower yields in the latest planted sweet corn may lead to the belief that density tolerance decreases as well, even if it does not.

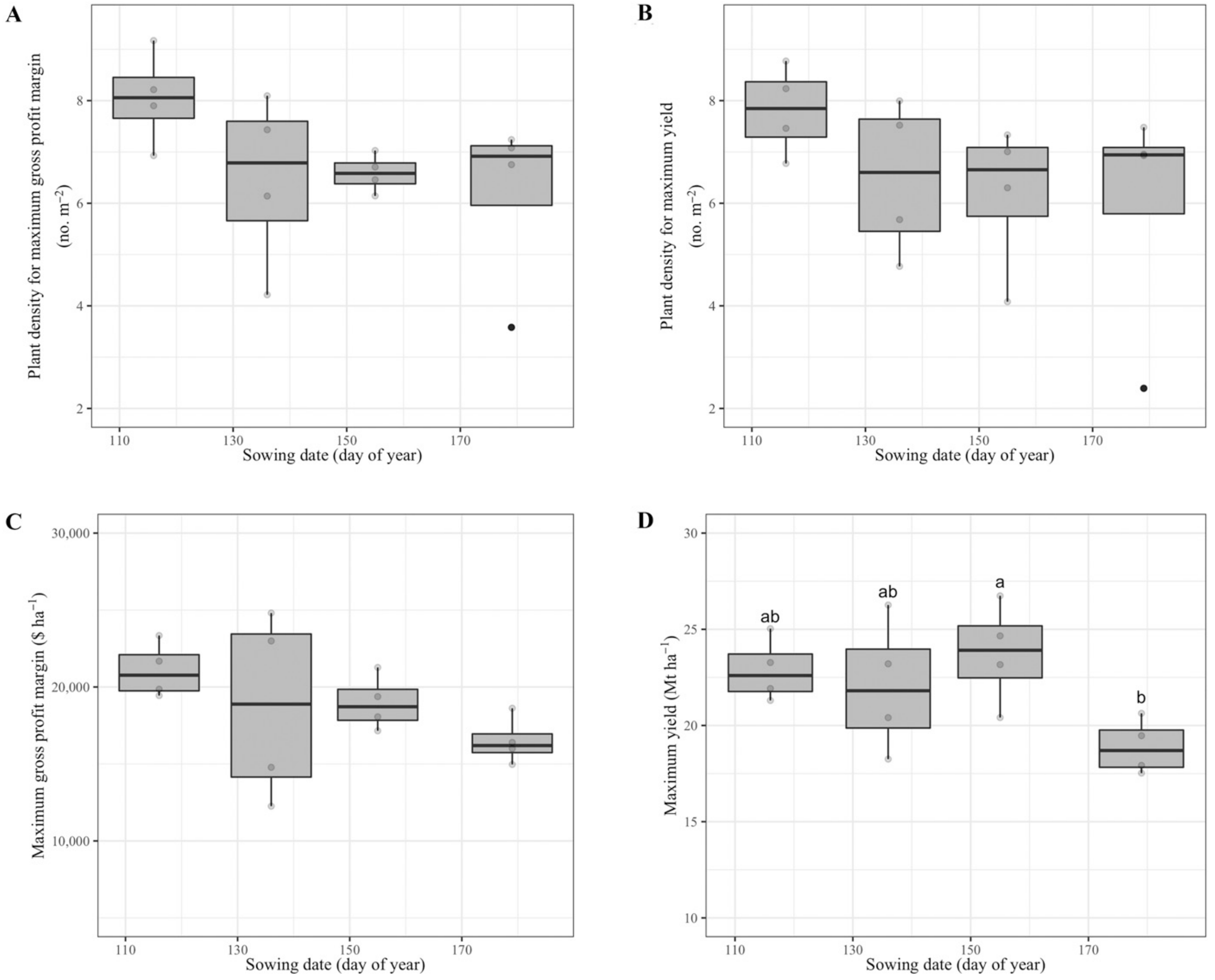

Fig. 4. Effect of the sowing date on (**A**) plant density for maximum gross profit margin, (**B**) plant density for maximum yield, (**C**) maximum gross profit margin, and (**D**) maximum yield. Distribution of responses across years and replicates within a sowing date are represented by boxplots. Sowing treatments with different responses are identified with unique letters above each boxplot.

Variation does exist in sweet corn optimum plant densities and is consistent with the findings of grain corn research (Assefa et al. 2016; Edwards 2016; Reeves and Cox 2013). That variation is likely driven by several factors other than the sowing date. As mentioned, hybrids differ in density tolerance, even among modern lines that are commercially available and grown (Williams 2012, 2015). The physiological underpinnings of density tolerance variations in sweet corn have received limited study (Choe et al. 2016, 2021; Revilla et al. 2021). Even within a hybrid, EOPD and YOPD can vary widely across environments (Dhaliwal and Williams 2019). Most likely, location-specific factors that describe the environment (e.g., weather, soils) or management (e.g., crop rotation, fertility) have a role; however, preliminary research has yet to identify the specific environmental conditions and management practices driving optimal population density (Dhaliwal and Williams 2020). Overturning the current industry perception—that density tolerance of sweet corn declines in late-season plantings—could be difficult without more extensive research that accounts for variations in optimum plant densities.

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